JLAB-PHY-01-31

Searching for Gluonic Excitations – The Hall D Project at Jlab

Elton S. Smith [a] *

[a]Jefferson Lab, Newport News, Va. 23606, USA

Abstract. Hybrid mesons are produced when the gluonic degrees of freedom are excited within normal mesons. A large fraction of these gluonic excitations can be identified using unique combinations of spin, parity and charge conjugation (J^{PC}) quantum numbers which are not allowed for ordinary $q\overline{q}$ bound states. Photon beams are expected to be particularly favorable for the production of such states, which are required by the quark confining mechanism of QCD. Mapping out the spectrum and decay modes of these hybrid mesons is the necessary first step in understanding the nature of confinement. Plans are underway at Jefferson Lab to upgrade the energy of the electron accelerator to 12 GeV. With 12 GeV electrons, a 9 GeV linearly polarized photon beam will be produced using the coherent bremsstrahlung technique. Along with this energy upgrade, a hermetic detector housed in new experimental hall (Hall D) will be used to collect data on photoproduced mesons with unprecedented statistics.

1. Introduction

In the early 1970s, evidence that the masses of strongly interacting particles increased without limit as their internal angular momentum increased led the theorist Yoichiro Nambu to propose that the quarks inside these particles are "tied together" by strings. Numerical simulations of QCD ("lattice QCD") have demonstrated that Nambu's conjecture was essentially correct: in chromodynamics, a string-like chromoelectric flux tube forms between distant static quarks, leading to their confinement with an energy proportional to the distance between them (see Fig. 1). The phenomenon of confinement is the most novel and spectacular prediction of QCD—unlike anything seen before. It is also the basic feature of QCD that drives all nuclear physics, from the mass of the proton and other nuclear building blocks to the NN interaction. For a popular discussion of this subject see Refs. [1,2].

The ideal experimental test of this new feature of QCD would be to study the flux tube directly by anchoring a quark and anti-quark a distance r apart ($\approx$ few fermis)

*Presented at the IV Latinamerican Symposium on Nuclear Physics, Colegio Nacional, Mexico D.F., September 24-28, 2001.

and examining the flux tube that forms between them. In such ideal circumstances one of the fingerprints of the gluonic flux tube would be its model-independent spectrum: two degenerate first excited states are the two longest-wavelength vibrational modes of this system, while their excitation energy is required to be π/r since both the mass and tension of this relativistic "string" arise from the energy stored in its color fields. Such a direct examination of the flux tube is, of course, not possible. In real life we have to contend with systems in which the quarks move. Fortunately, we know both from general principles and from lattice QCD calculations that an approximation to the dynamics of the full system works extremely well—at least down to quark masses of the order of 1 GeV.

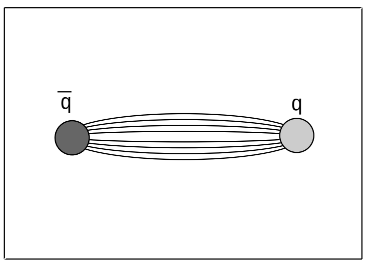

Figure 1. Flux tube between static quarks.

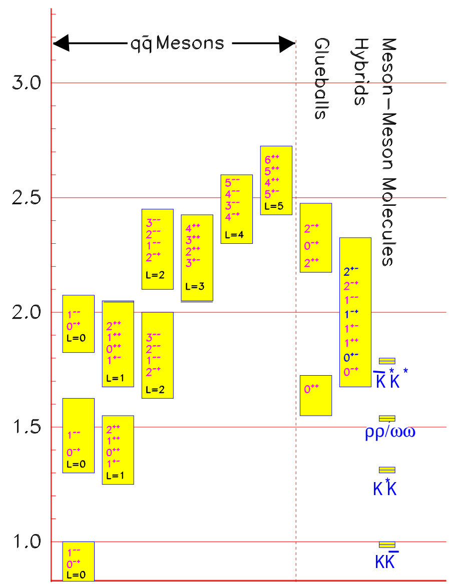

Figure 2. Excitation spectrum of the $q\bar{q}$ spectrum(left) and gluonic and molecular states (right).

Models are required to extend this firm understanding to yet lighter quarks, but the most important properties of this system are determined by the model-independent features described above. In particular, in a region around 2 GeV, a new form of hadronic matter must exist in which the gluonic degrees-of-freedom of a quark-antiquark system are excited (see Fig. 2). The smoking gun characteristic of these new states is that the vibrational quantum numbers of the gluonic "string," when added to those of the quarks, can under certain circumstances produce quantum numbers (total angular momentum J, a total parity P, and total charge conjugation symmetry C) which are not allowed for ordinary $q\overline{q}$ states. These unusual J^{PC} combinations (such as 0^{+-}, 1^{-+}, and 2^{+-}) are called exotic, and the states are referred to as exotic hybrid mesons. Not only general considerations and flux tube models, but also first-principles lattice QCD calculations, require that these states have masses around 2 GeV; furthermore, they demonstrate that the levels and their orderings will provide experimental information on the mechanism that produces the flux tube.

2. Exotic production with photons

Photon beams are expected to be particularly favorable for the production of the exotic hybrids [4]. The reason is that the photon sometimes behaves as a "virtual vector meson" with total quark spin $S = 1$. When the flux tube in this $S = 1$ system is excited, both ordinary and exotic J^{PC} are possible. In contrast, when the spins are anti-parallel ($S = 0$), as in pion or kaon probes, the exotic combinations are not generated. To date, most meson spectroscopy has been done with incident pion, kaon, or proton probes, so it is not surprising that the experimental evidence to date for flux tube excitation is tentative. In contrast to hadron beams, high-flux photon beams of sufficient quality and energy to perform meson spectroscopy studies have not been available, so there are virtually no data on photoproduction of mesons with masses in the 1.5 to 3 GeV region. Thus, experimenters have not been able to search for exotic hybrids precisely where they are expected to be found.

The optimal photon beam energy is set by several considerations. The interest lies in the mass range from 1.0 GeV/c^2 up to about 2.7 GeV/c^2, the region where light quark hybrids are expected to exist. Incident photon energies of 9 GeV are sufficient to access this mass range, and are achievable starting with 12 GeV electrons. The photon beam will be produced using the coherent bremsstrahlung technique. At special settings for the orientation of the crystal radiator, the atoms of the crystal can be made to recoil together from the radiating electron leading to an enhanced emission at particular photon energies, and yielding linearly polarized photons. The position of the coherent peak changes as one adjusts the angle of the crystal planes with respect to the electron direction. Moreover, there is a correlation of the angle of the emitted photon with energy. This correlation can be exploited using collimation to reduce the incoherent background (see Fig. 3). For a typical crystal orientation, the resulting spectrum after collimation produces a photon energy peak at 9 GeV. The average degree of linear polarization in the peak is 40 percent. In addition, the photons emitted in a 0.5 GeV-wide window will be tagged using a magnetic spectrometer.

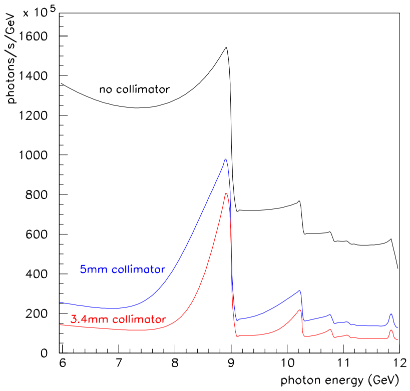

Figure 3. The coherent bremsstrahlung peak is enhanced by collimation. Photons in the peak have a linear polarization of 40%.

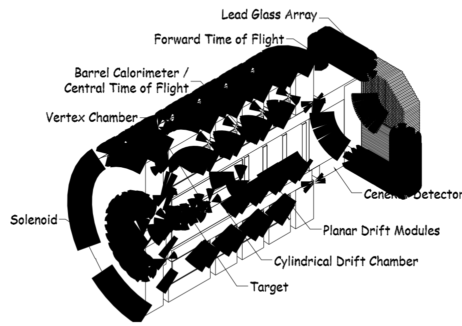

Figure 4. Schematic view of the Hall D detector.

3. The Hall D detector

The Hall D detector (see Fig. 4) has been optimized to provide nearly hermetic acceptance for charged particles and photons [3]. In addition, a combination of particle identification systems will allow very good K-π separation. The full reconstruction of exclusive many-body final states is accomplished with a variety of detector subsystems. In conjunction with high statistics, this will allow us to do excellent partial wave analysis for many final states. The detector configuration is based on the geometry of a large superconducting solenoidal magnet, which is ideally suited for a high-flux photon beam. The electromagnetic charged particle background from interactions in the target is contained within the beam pipe by the axial field of the magnet. The liquid hydrogen target is located along the axis, somewhat upstream of center. It is surrounded by a cylindrical array of scintillator strips and scintillating fibers within an outer array of straw tube drift chambers. These are surrounded by a barrel calorimeter. Within the solenoid and downstream of the target are planar tracking chambers. Downstream of the solenoid is an atmospheric gas Cerenkov counter followed by a time-of-flight wall and then an array of lead glass that forms an electromagnetic calorimeter. The detector is equipped with a fully pipelined system of electronics in the trigger, digitizer and data-acquisition system to handle the expected photon flux.

4. Performance

The performance of the detector and the flux and linear polarization of the photon beam determine the level of sensitivity for mapping the hybrid spectrum. A double-blind exercise was carried out in which an exotic signal, a $J^{PC} = 1^{-+}$ state with a mass of 1.6 GeV/c^2 decaying into $\rho\pi$, was generated along with a mix of three well-established non-exotic states with masses of 1.2, 1.3 and 1.7 GeV/c^2. In this exercise the exotic signal was generated at the level of 2.5% of the total sample. The momenta of the decay products of these particles were smeared according to the expected resolution of the detector. The acceptance of the detector was also applied. The resulting data set was passed through a partial wave analysis (PWA) fitting procedure to determine the relative contributions of each wave. The plot in Fig. 5 shows the input exotic wave as a solid curve and the result of the PWA fit as points with error bars. The input wave is reproduced extremely well, and this demonstrates the capabilities of the detector and sensitivity of the experiment.

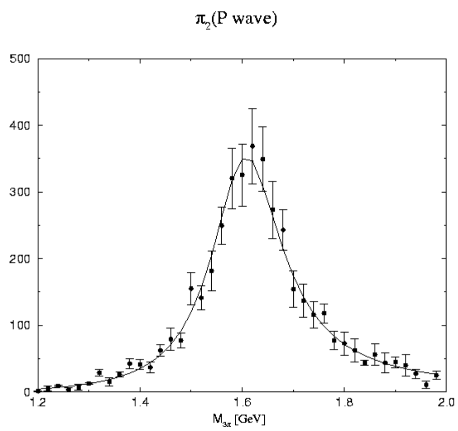

Figure 5. Exotic signal extracted from simulated data using a partial wave analysis. The smooth curve corresponds to the input signal and the points with error bars corresponds to the fit.

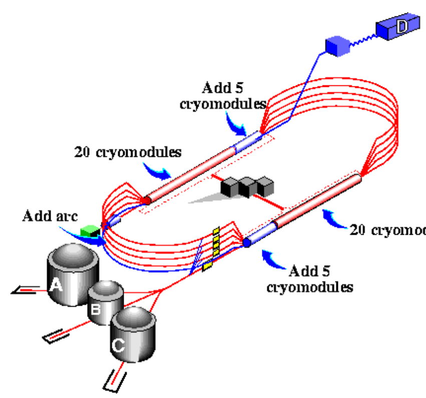

Figure 6. Schematic of the accelerator configuration for the proposed 12 GeV upgrade.

5. Energy Upgrade

The electron accelerator at Jefferson Lab (Fig. 6) consists of a pair of interconnected linacs, each comprising 20 cryomodules, with each cryomodule containing eight superconducting radiofrequency (SRF) accelerating cavities [4]. On average, these cavities have exceeded their original design specification by 50%. It is the success of this technology that has opened up the possibility of a simple and relatively inexpensive upgrade of the current energy of 6 GeV to 12 GeV. With expected further improvements in SRF technology and with the production of a new compact cryomodule based on seven-cell cavities, doubling the energy of the machine can be attained at modest cost. Straightforward modifications of the re-circulating arcs will accommodate the higher energies. Finally, an additional arc will be added to allow for one more pass of the beam through one linac to deliver beam to Hall D.

6. Conclusions

The Hall D project makes use of recent developments in beam and detector technology to definitely map out the hybrid spectrum of mesons. The beam and detector have been optimized to perform a complete partial wave analysis of mesons produced with an 8 to 9 GeV linearly polarized photon beam. When the spectrum of decay modes of these gluonic excitations have been mapped out experimentally, we will have a made a giant step forward in understanding one of the most important phenomena discovered in the twentieth century: quark confinement.

Acknowledgement(s)

I would like to thank the organizers of the conference for creating a pleasant atmosphere conducive to the exchange of scientific ideas. I also wish to acknowledge my Hall D collaborators, especially Alex Dzierba and Adam Szczepaniak. This work is supported in part by the U.S. Department of Energy, including DOE Contract No. DE-AC05-84ER40150.

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